AEROSPACE
Assuring Space Mission Success

Deferral Estimation Analysis Study

Dean A. Bucher

NASA Cost Symposium
25-27 August 2015

Introduction

Deferral Estimation Analysis

- Background
  - *Over the past few years, Aerospace has performed multiple studies to understand the drivers that cause cost and schedule growth in NASA projects including the Explanation of Change (EoC) and 40-Mission Studies*
  - *In an effort to build upon these prior studies, the NASA Cost Analysis Division (CAD) funded Aerospace to investigate the factors that lead to cost and schedule growth when a project's funding is deferred or constrained*

- Rationale
  - *In today's economic environment, funding delays are becoming commonplace for many NASA (and DoD) projects*
  - *Budgeting exercises often require quick responses to adjustments in funding profiles due to constraints/offsets/external direction*
  - *Full cost and schedule impacts resulting from such funding delays are not yet adequately understood*

Objective

Deferral Estimation Analysis

- Objective of Study
  - *Expand on the work completed to date with an emphasis on the correlation between deferred funding and cost and schedule growth*
    - Investigate the cost and schedule impacts of deferred funding on NASA missions with known funding cuts
  - *Apply Aerospace's General Error Regression Model (GERM) to the data collected and generate a series of "Rules of Thumb" to address the impacts of deferred funding on future projects*
    - Identify and segregate cost and schedule impacts driven by funding cuts
    - Identify multivariable relationships that display high correlation to collected funding reduction data
  - *Identify useful metrics to begin tracking in other data sets (such as CADRes)*

- Study Approach
  - *Phase 1: Survey of Historical Funding Profiles*
  - *Phase 2: Deferred Funding Impacts "Rules of Thumb"*

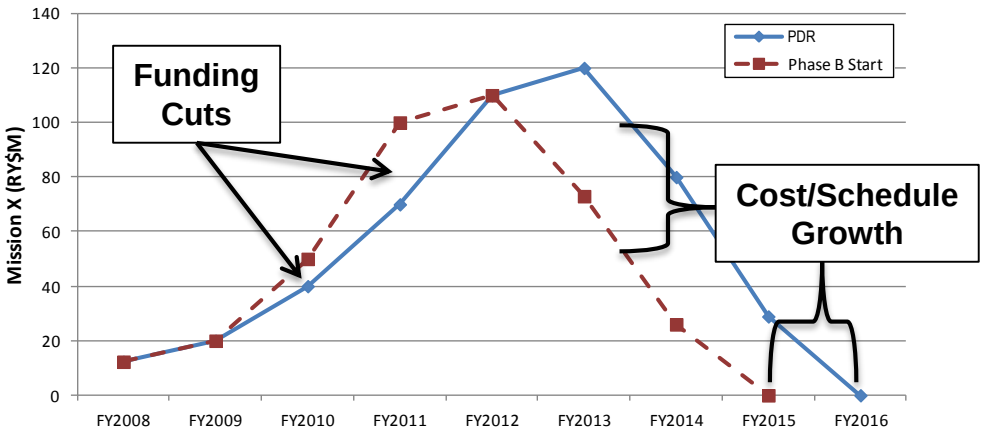
Phase 1: Survey of Historical Funding Profiles

Phase 1: Survey of Historical Funding Profiles

Deferral Estimation Analysis

- Approach
  - *Leveraging EoC, CADRe, and mission milestone data sets, funding profile data was evaluated for NASA missions that have experienced deferred or constrained funding during development*
    - Data was collected for the total mission, at the WBS element level (PM/SE/MA, Spacecraft, and Instrument), and by phase
      - *Includes data at various milestones throughout development as well as actuals at launch*
    - Cost and schedule impacts were then quantified for identified funding reductions just prior to and after the funding cut occurred
  - *Data was used to identify relationships between deferred funding and total cost/schedule growth (including the timing and magnitude of funding cuts)*

- Mission Set
  - *Launched*
    - Aquarius
    - Juno
    - Kepler
    - OCO
    - SDO
    - WISE
    - SMAP
  - *In Development*
    - GRACE FO
    - ICESat-2
  - *Removed**
    - OCO-2

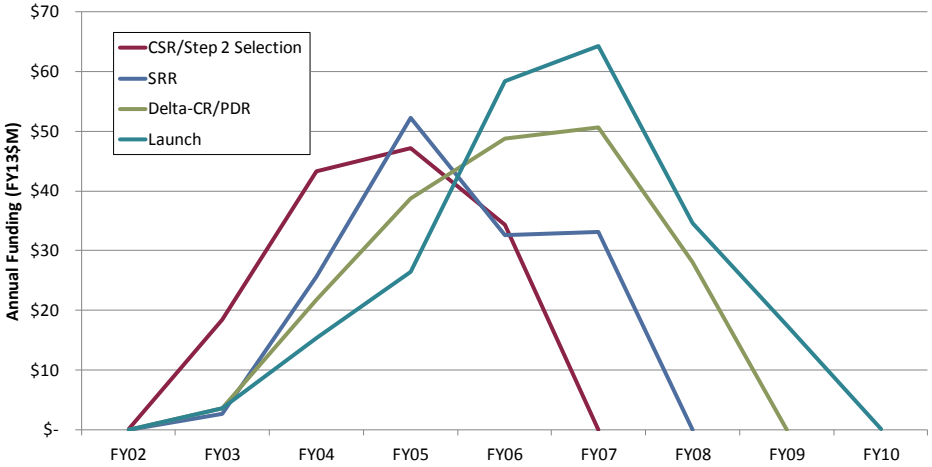


* OCO-2 missions removed from dataset after further investigation

AEROSPACE

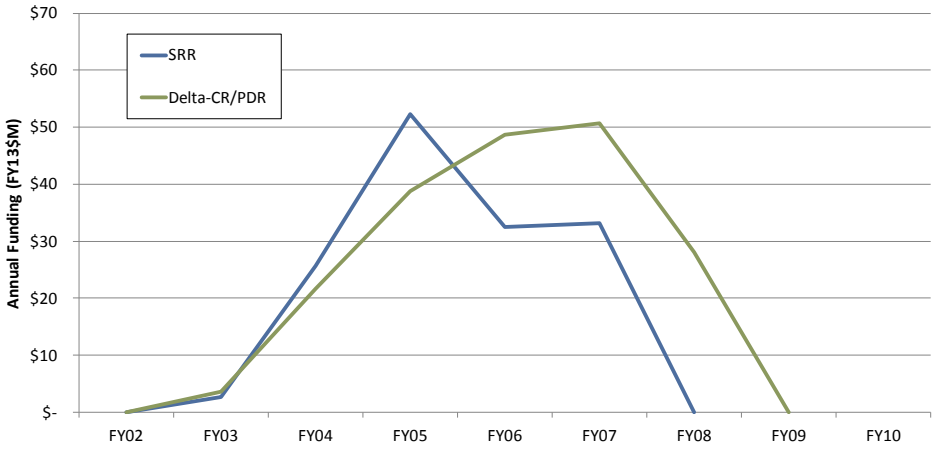
Funding Reduction Identification

Methodology



- Potential budget cuts were determined by comparing funding profiles from Project milestone data (CADRes)
- Budgets before and after suspected cuts were isolated and analyzed
  - *In this example, funding cuts identified early in Phase B were compared to the SRR budget*

- Multiple metrics were then quantified for each identified funding reduction to represent a collection of both dependent and independent variables
  - *Necessary to facilitate multivariable regression for Phase 2*



Phase 1 Metrics

Deferral Estimation Analysis

- Independent Variables
  - *Funding reduction magnitude*
    - Total Reduction – Reduction relative to initial budget
    - Current Year % – % funding reduction over the fiscal year affected by the cut
      - *If multiple fiscal years were affected, an average of those years is used*
  - *Reduction timeline*
    - Notification – Time relative to Phase B start when project was notified there would be a funding cut
    - Reduction Start – Time relative to Phase B start when funding cut began
    - Reduction End – Time relative to Phase B start when funding cut ended
    - Reduction Span – Difference between Reduction Start and Reduction End, representing time span of reduction
  - *Development cost and schedule*

- Dependent Variables
  - *Cost Growth*
    - Cost growth during Phase B, Phase C, Phase D, and Phase B-D cost growth
  - *Schedule Growth*
    - Schedule growth during Phase B, Phase C, Phase D, and Phase B-D schedule growth

Phase 2: Deferred Funding Impacts “Rules of Thumb”

Phase 2: Deferred Funding Impacts “Rules of Thumb”

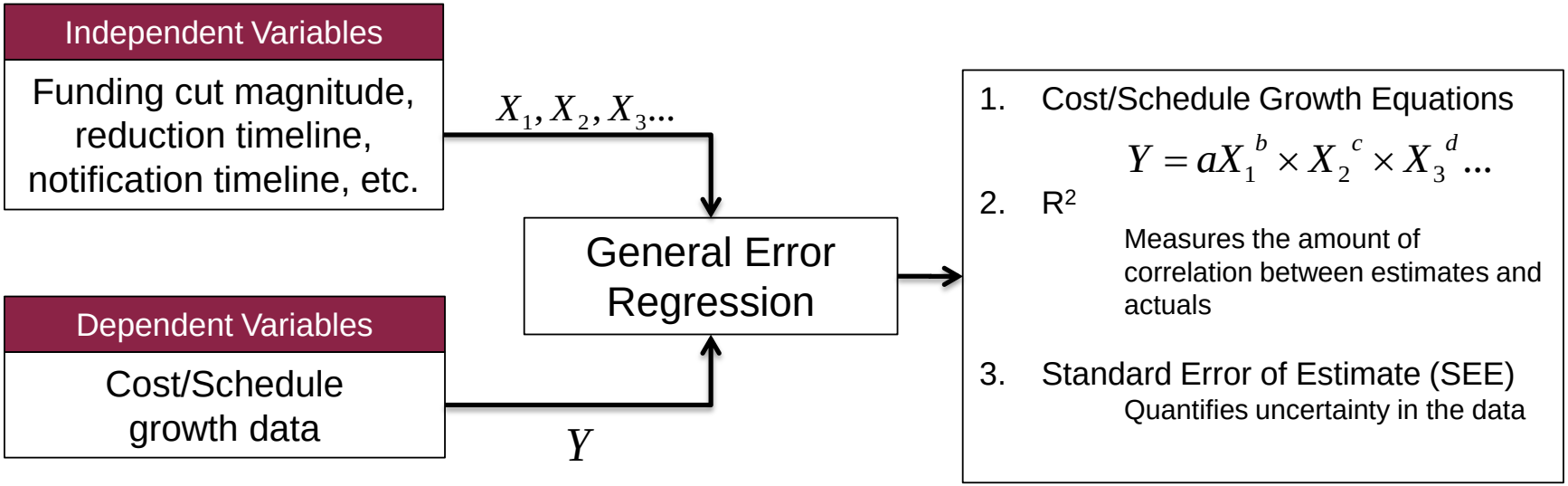
Deferral Estimation Analysis

- Approach
  - *Phase 2 applies Aerospace’s General Error Regression Model (GERM) to the data collected in Phase 1 to generate a series of “Rules of Thumb” to address the impacts of deferred funding on future projects*
    - Identify multi-variable relationships that display high correlation to the collected funding reduction data from Phase 1
      - *Independent variables: funding cut magnitude, reduction timeline, notification timeline, etc.*
      - *Dependent variables: schedule growth, cost growth, etc.*
    - Perform sensitivity analyses to identify “Rules of Thumb”

- Objective
  - *Develop “Rules of Thumb” to answer the following questions:*
    - For each dollar deferred in year X, what is the increase in development cost and delay in LRD?
    - When is the optimal point in a project’s development to reduce funding in order to minimize the long-term impacts to cost and schedule?
    - Is there a threshold where the magnitude of a funding reduction results in significantly higher cost and/or schedule growth?
    - Is there a funding profile resistant to the impact of deferred funding?

General Error Regression Model (GERM)

Methodology



- Begin with a single variable, X_1
- Examine additional cost growth or schedule growth drivers (X_2, X_3, etc.) until the best statistical values are obtained
- Verify the quality of the equations based on the values of R^2 and SEE and regression coefficients

Phase 2 Regression Results

Deferral Estimation Analysis

- Based on the data collected in Phase 1, the Phase 2 regression effort produced results for four different growth metrics
  - *Project Cost Growth*
  - *Project Schedule Growth*
  - *Spacecraft Cost Growth (backup)*
  - *Instrument Cost Growth (backup)*

- Each of the four metrics utilize the same basic regression formula:

$$Y = A * X_1^{\,B} * X_2^{\,C} * X_3^{\,D} * X_4^{\,E}$$

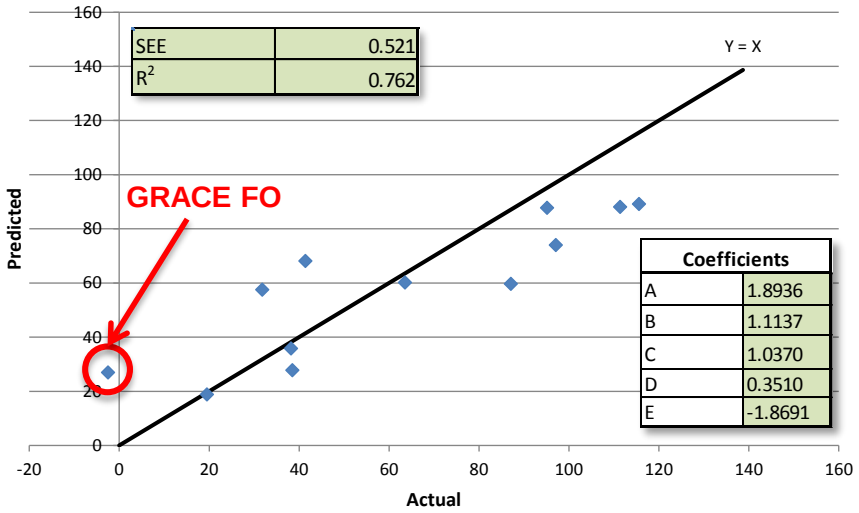
- Important Definitions
  - *WBS Definitions*
    - Project: Project total minus Launch Vehicle
    - Spacecraft: Spacecraft and Flight System I&T total
    - Instrument: Instrument WBS total; does not distinguish between individual instruments
  - *Dependent Variable Definitions*
    - Cost Growth: Phase B-D cost growth at the applicable WBS level in FY14$M
    - Schedule Growth: Phase B-D duration growth (Project-level only)

IMPORTANT: Results DO NOT segregate between cost/schedule growth due solely to a funding reduction and growth due to other influences

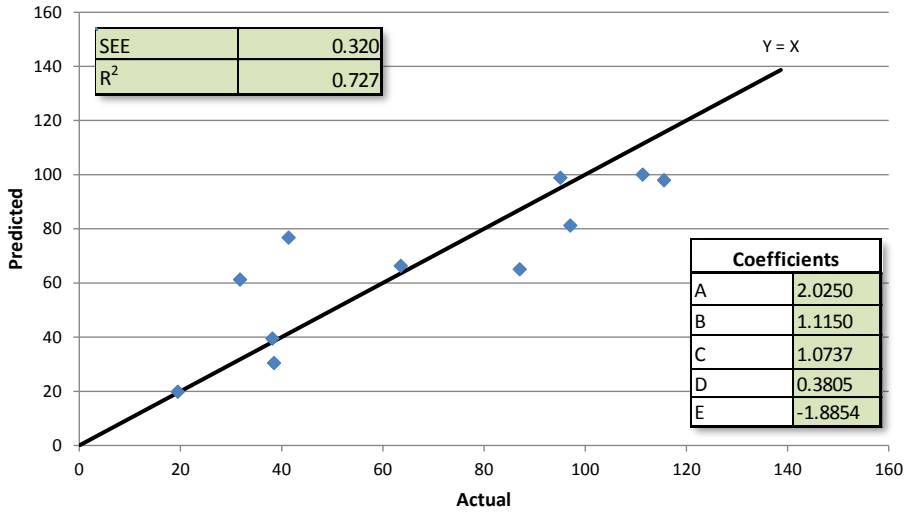
Project Cost Growth

Phase 2 Regression Results

Outliers Included



Outliers Excluded

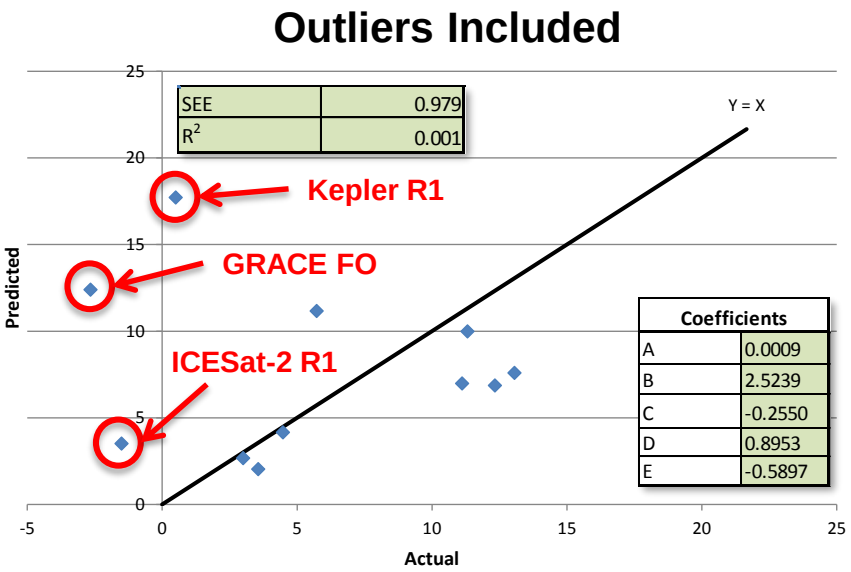


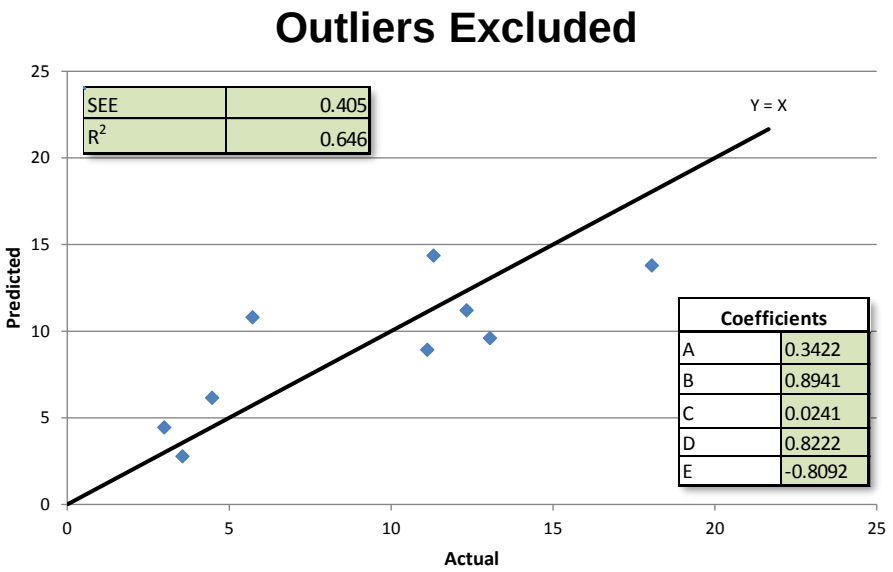
Cost Growth (FY14$M) = 2.03 * Development Cost (FY14$M) $^{1.11}$ * Total % Reduction $^{1.07}$ * Reduction (phase) $^{0.38}$ * Span (mo) $^{-1.89}$

- **Independent Variable Definitions**
  - *Development Cost (FY14$M): Phase B-D cost at the applicable WBS in FY14$M*
  - *Total % Reduction = Total Reduction in FY14$M / Development Cost in FY14$M*
    - Total Reduction in FY14$M: In only the year(s) being cut, the sum total of the reduction
  - *Reduction (phase): Development phase in which the reduction will occur*
    - Phase A = 0.25, Phase A/B = 0.375, Phase B = 0.50, Phase B/C = 0.625, Phase C = 0.75
  - *Span (mo): Span in months of the reduction (i.e. if the reduction is to occur in FY16-17, the span is 24 months)*

Project Schedule Growth

Phase 2 Regression Results





Schedule Growth (mo) = 0.34 * Phase B-D Schedule (mo)$^{0.89}$ * Development Cost (FY14$M)$^{0.02}$ * Total % Reduction$^{0.82}$ * Span (mo)$^{-0.81}$

- **Independent Variable Definitions**
  - *Phase B-D Schedule (mo): Phase B-D planned duration in months*
  - *Development Cost (FY14$M): Phase B-D cost at the applicable WBS in FY14$M*
  - *Total % Reduction = Total Reduction in FY14$M / Development Cost in FY14$M*
    - Total Reduction in FY14$M: In only the year(s) being cut, the sum total of the reduction
  - *Span (mo): Span in months of the reduction (i.e. if the reduction is to occur in FY16-17, the span is 24 months)*

Outliers in the schedule growth data created significant challenges to the Phase 2 regression effort

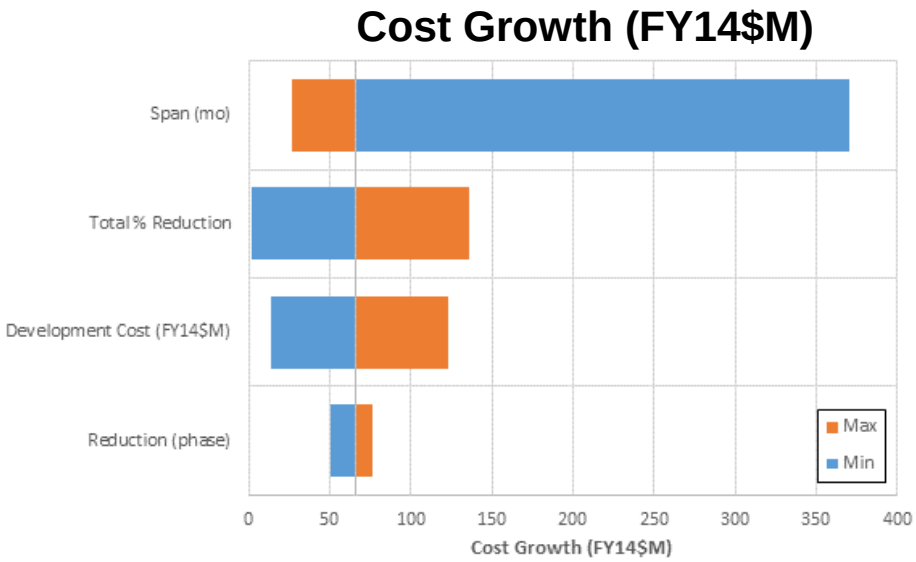
Phase 2 Results Sensitivity Analysis

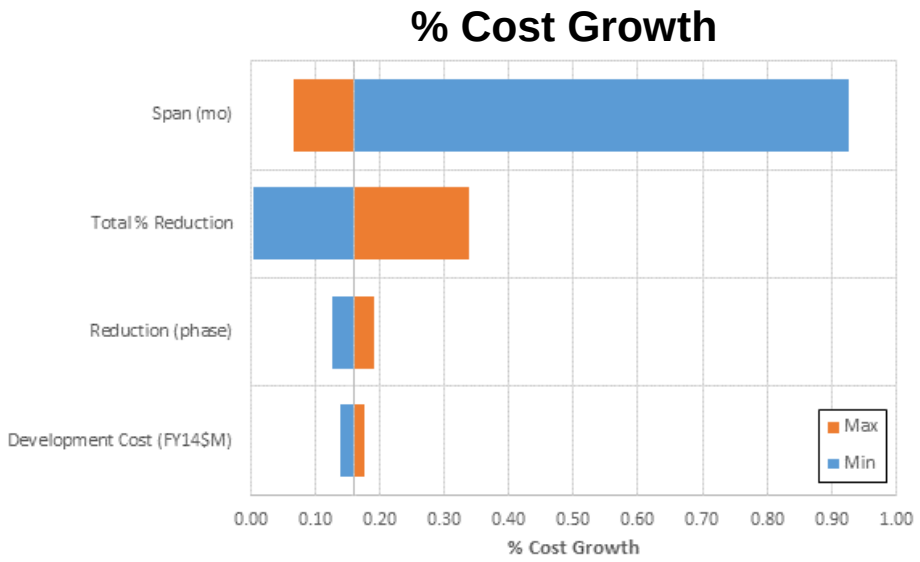
Deferral Estimation Analysis

- In order to better understand the applicability, utility, and robustness of the Phase 2 regression results, a sensitivity analysis was conducted on each of the four regression equations
  - *Simple Sensitivity Analysis*
    - Implemented the one-factor-at-a-time (OFAT) sensitivity analysis approach relative to the full range of the appropriate WBS dataset
    - Independent variables were varied one-at-a-time between the minimum, mode, and maximum values while the remaining variables were held fixed at the mode
    - Although this analysis is a simple approach to identify the key drivers in each equation, OFAT does not explore the full input space of the model
  - *Monte Carlo Analysis*
    - In order to fully explore the input space of each regression equation, a Monte Carlo analysis was also conducted
    - All independent variables were varied across a uniform distribution in a 10,000-iteration Monte Carlo analysis and evaluated relative to impacts on cost and schedule growth
  - *Compounding Variables*
    - Based on the results of the Monte Carlo Analysis, areas of extreme cost and schedule growth were investigated to identify the contributing factors
    - As a result, compounding variable combinations producing unrealistic cost and schedule growth were identified and compared to real-world applications

Project Cost Growth Sensitivity

Phase 2 Results Sensitivity Analysis





- **Applicable Range**

Independent Variables	Min	Max
Development Cost (FY14$M)	100	700
Total % Reduction	1	50
Reduction (phase)	0.25	0.75
Span (mo)	12	48

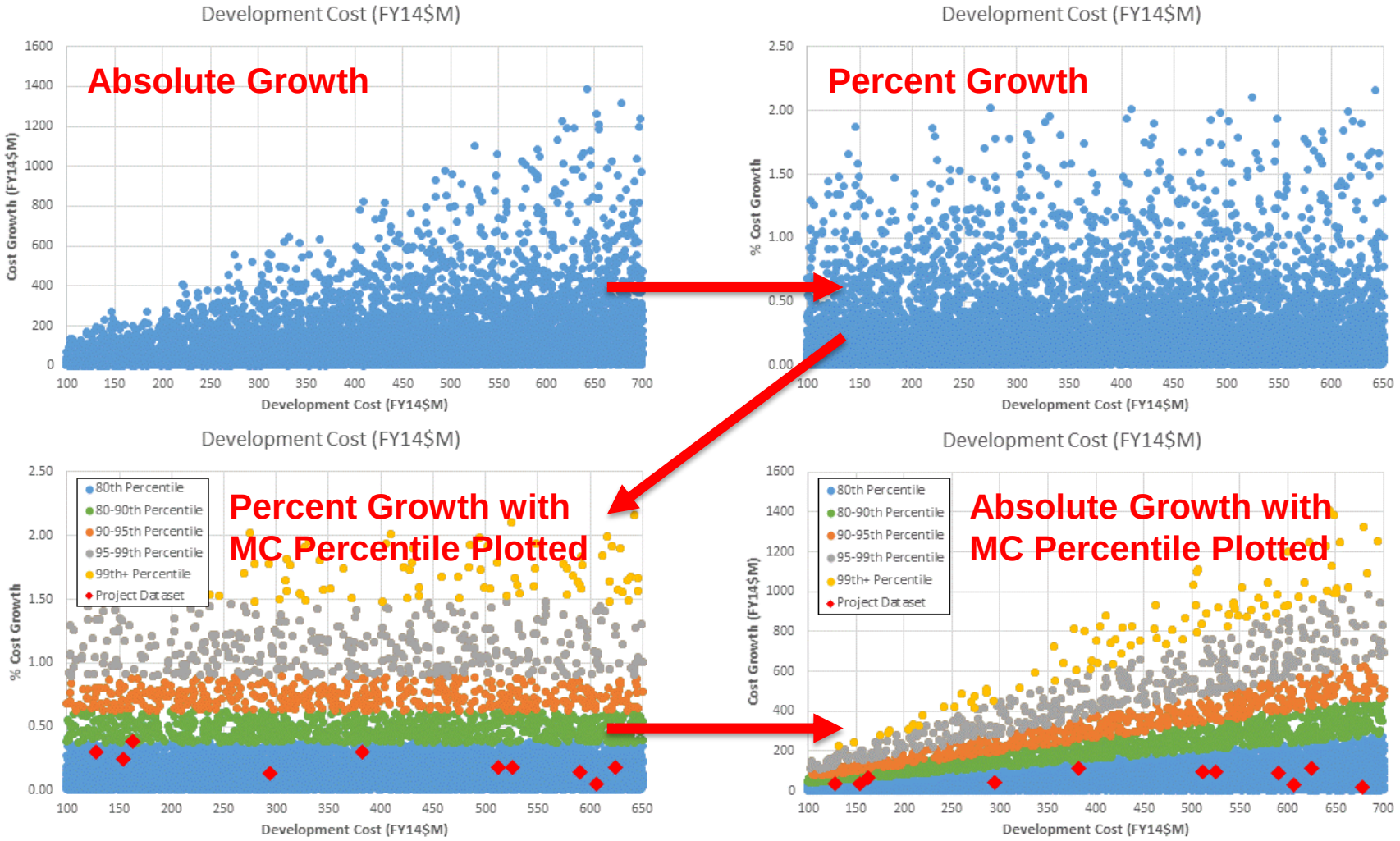
- **Sensitivity Analysis**
  - *Cost growth at the Project level shows significant sensitivity to the span of time across which funding cuts are applied*
  - *Second largest driver to cost growth is the magnitude of the funding cut in % reduction*

$$\textbf{Cost Growth (FY14\$M)} = 2.03 * \textbf{Development Cost (FY14\$M)}^{1.11} * \textbf{Total \% Reduction}^{1.07} * \textbf{Reduction (phase)}^{0.38} * \textbf{Span (mo)}^{-1.89}$$

AEROSPACE

Introduction to Monte Carlo Analysis

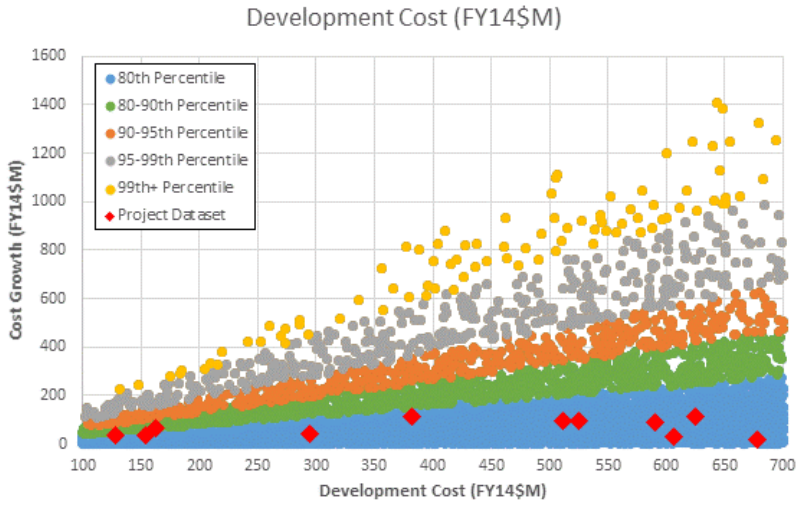
Phase 2 Results Sensitivity Analysis

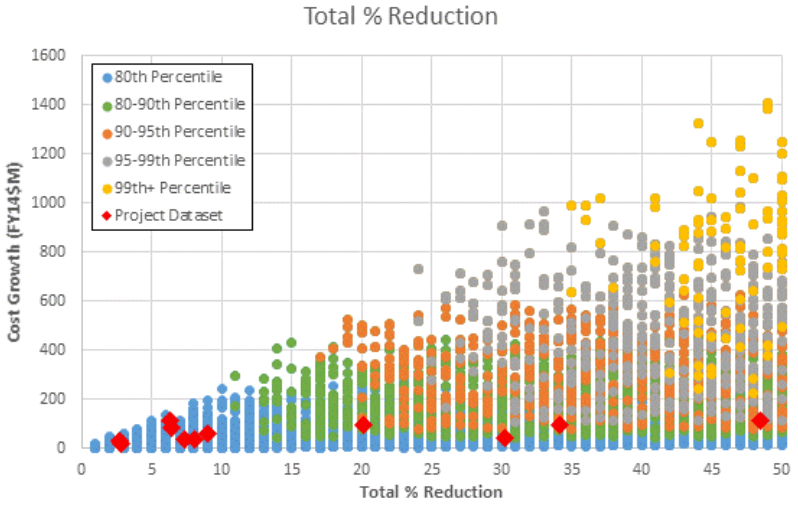


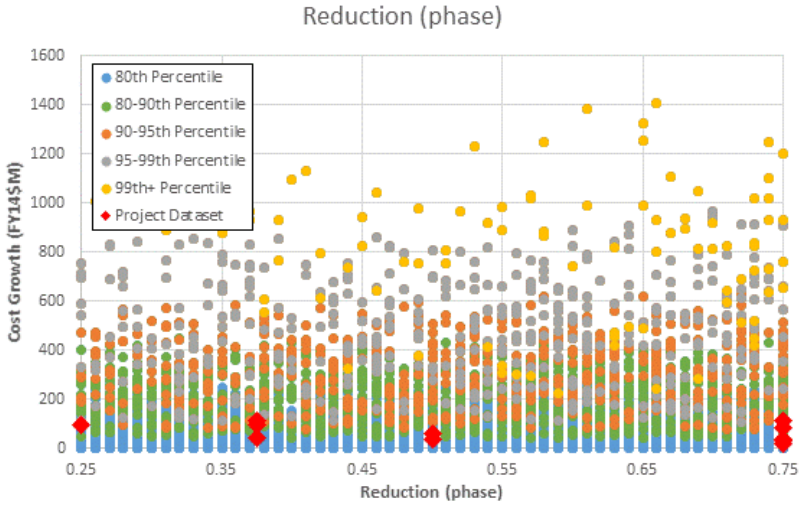
For the Monte Carlo analysis, each variable was varied across the applicable range and plotted against both the absolute growth and % growth dependent variables

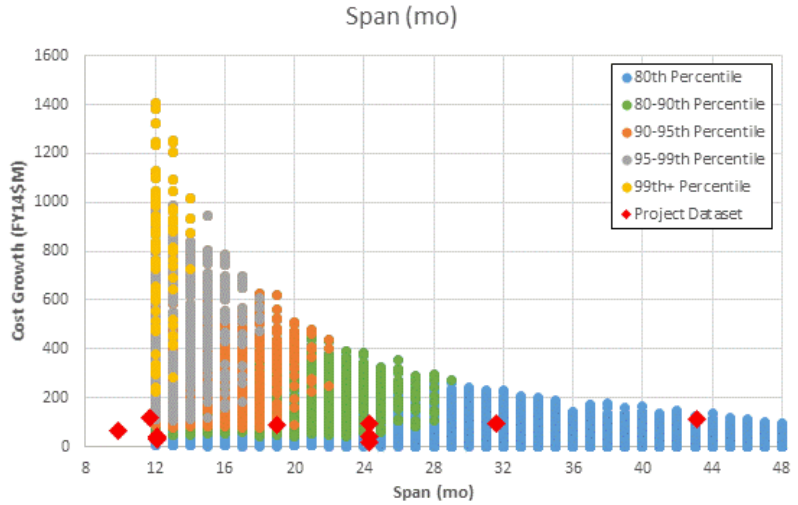
Project Cost Growth Monte Carlo Analysis

Phase 2 Results Sensitivity Analysis







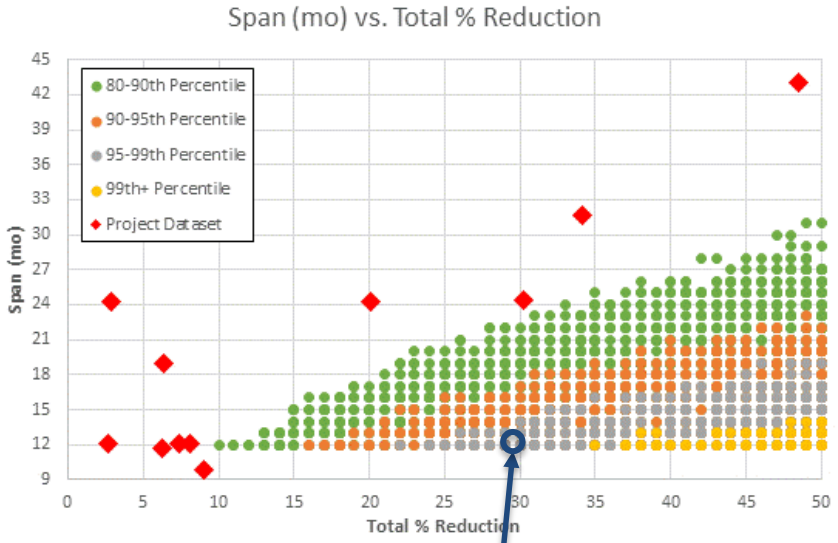


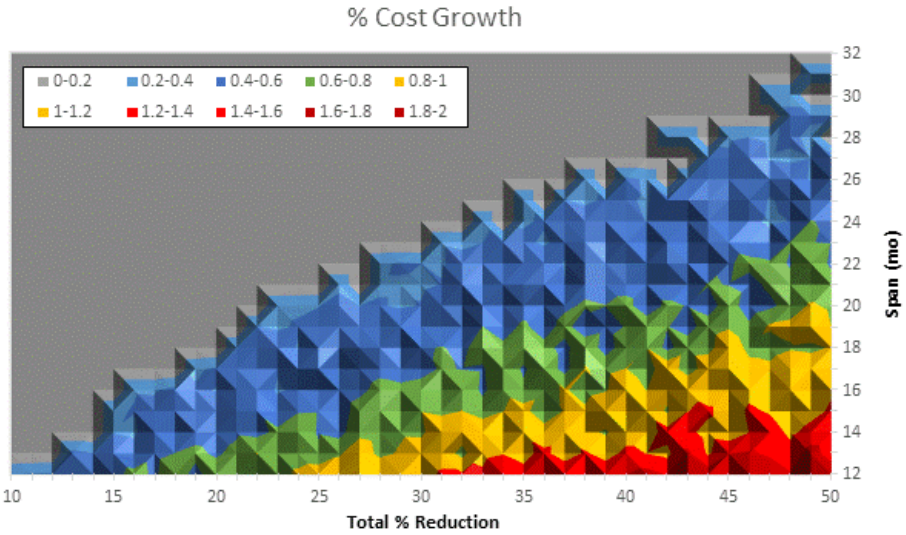
Top 20th percentile of the cost growth Monte Carlo sensitivity results appear outside the limits of the Project-level dataset

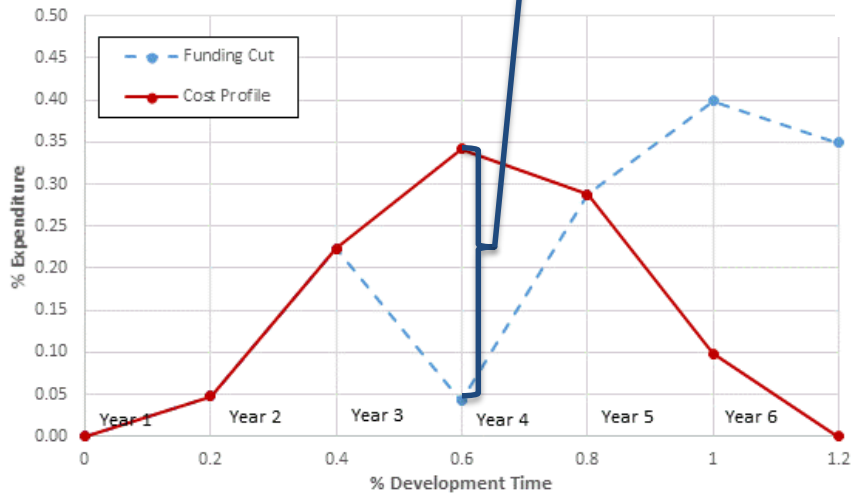
AEROSPACE

Project Cost Growth Compounding Variables

Phase 2 Results Sensitivity Analysis







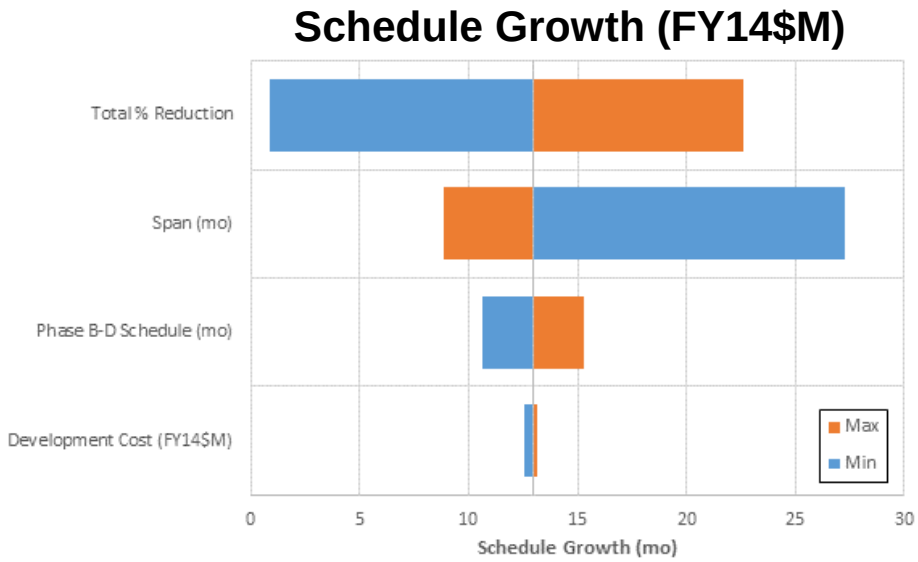
- **Impact of Compounding Variables**
  - *Top 20th percentile of Monte Carlo cost growth results are driven by unrealistic combinations of the % funding reduction and the span of the reduction*
  - *When these combinations are compared to a notional funding profile (bottom left), the detrimental impacts of such high reductions over relatively short spans of time become apparent*

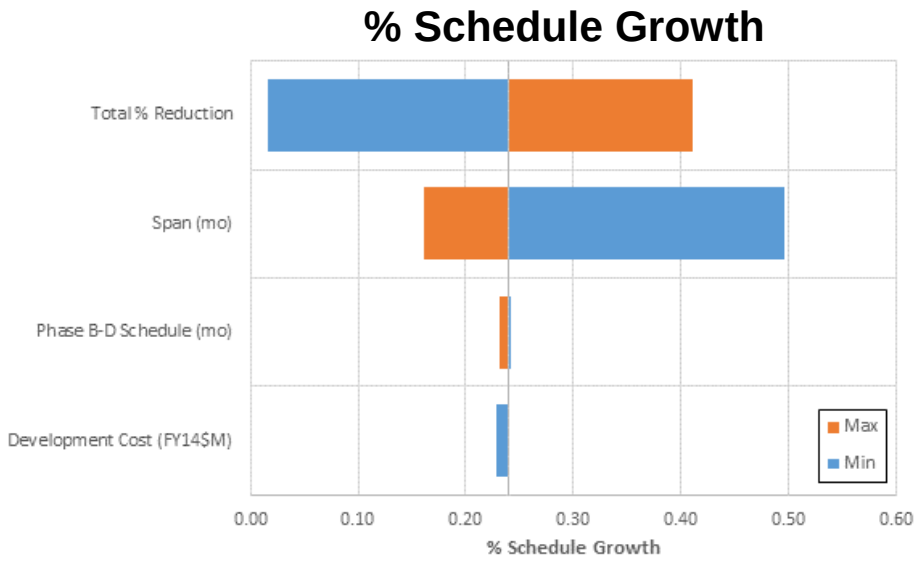
Application of a 12% or greater funding reduction will result in extreme Project cost growth estimates unless spread over multiple years

AEROSPACE

Project Schedule Growth Sensitivity

Phase 2 Results Sensitivity Analysis





- **Applicable Range**

Independent Variables	Min	Max
Phase B-D Schedule (mo)	44	66
Development Cost (FY14$M)	100	700
Total % Reduction	1	50
Span (mo)	12	48

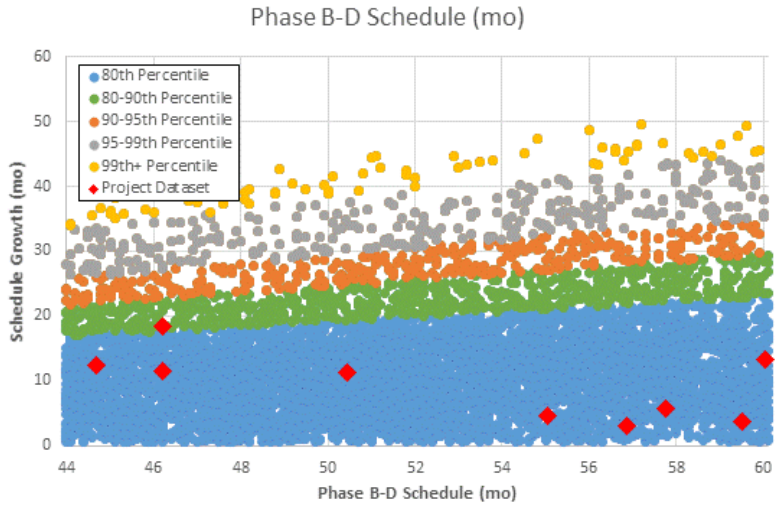
- **Sensitivity Analysis**
  - *Schedule growth at the Project level shows the most sensitivity to the magnitude of the funding cut in % reduction*
  - *Second largest driver (by a small margin) is the span of time across which funding cuts are applied*

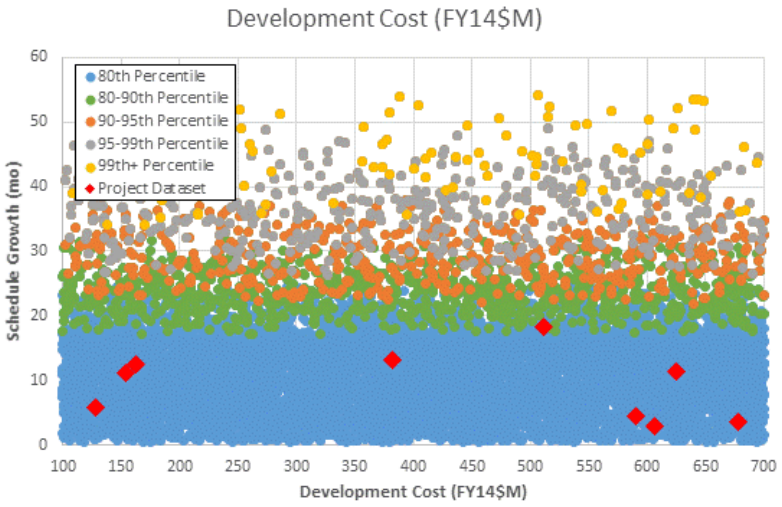
$$\textbf{Schedule Growth (mo)} = 0.34 * \textbf{Phase B-D Schedule (mo)}^{0.89} * \textbf{Development Cost (FY14\$M)}^{0.02} * \textbf{Total \% Reduction}^{0.82} * \textbf{Span (mo)}^{-0.81}$$

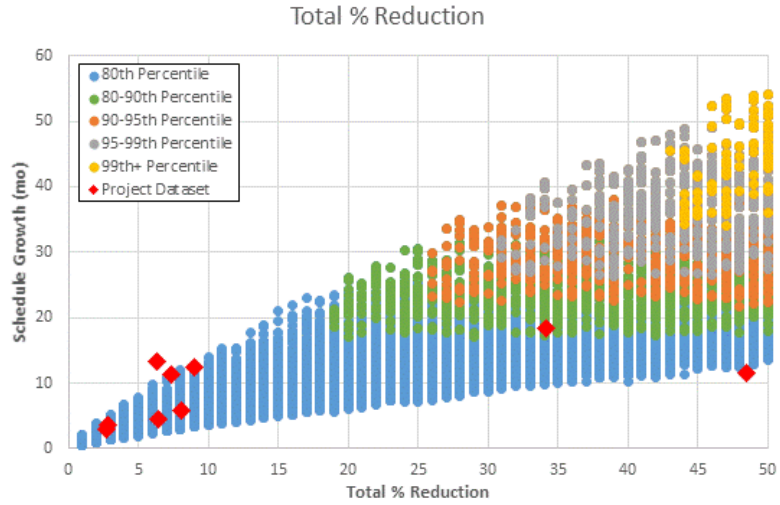
AEROSPACE

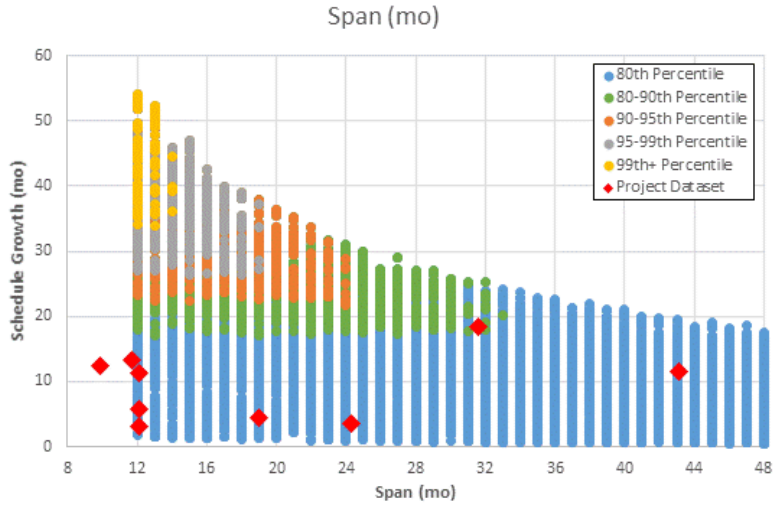
Project Schedule Growth Monte Carlo Analysis

Phase 2 Results Sensitivity Analysis





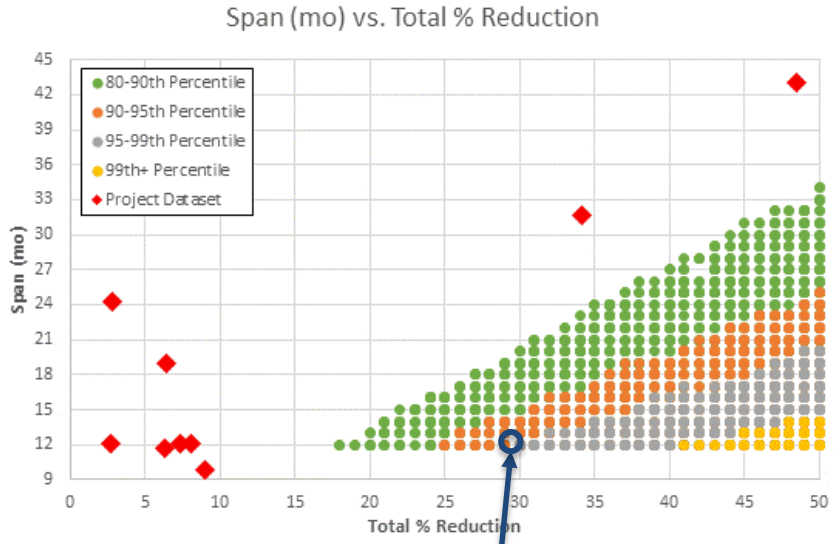


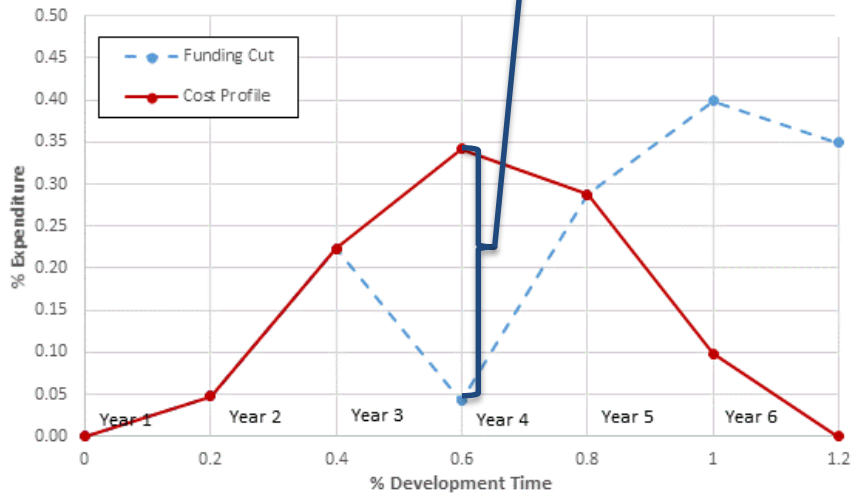


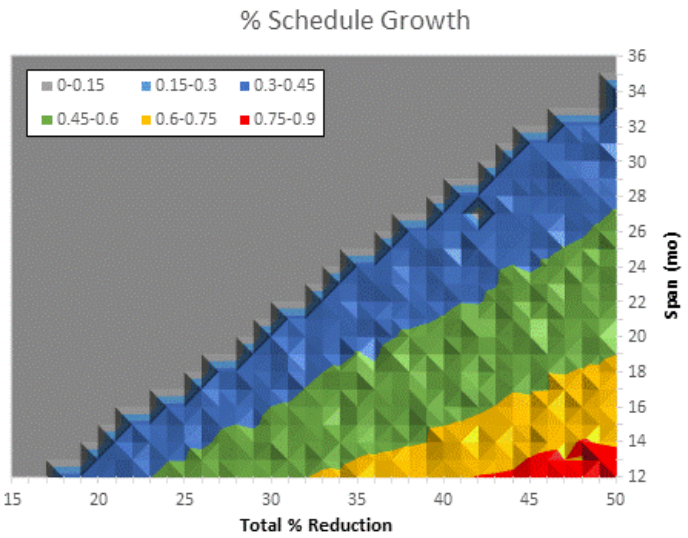
Consistent with the cost growth sensitivity, top 20th percentile of the Project schedule growth sensitivity results appear outside the limits of the Project-level dataset

Project Schedule Growth Compounding Variables

Phase 2 Results Sensitivity Analysis







- **Impact of Compounding Variables**
  - *Similar to the Project cost growth results, the top 20th percentile of Monte Carlo results are driven by unrealistic combinations of the % funding reduction and the span of the reduction*
  - *Application of a 20% or greater funding reduction will result in extreme schedule growth estimates unless spread over multiple years*

Project cost growth sensitivity to combinations of % funding reduction and span is greater than the schedule growth sensitivity

AEROSPACE

Phase 2 “Rules of Thumb”

Deferral Estimation Analysis

- Based on Phase 2 regression results and sensitivity analysis, 4 independent variables consistently produced the highest R^2 and lowest SEE and were identified as key drivers
  - *Development Cost (FY14$M)*
  - *Total % Reduction*
  - *Reduction Span (months)*
  - *Reduction Timing (phase)*

- Combinations of high funding reductions implemented over shorter spans of time result in extreme cost and schedule growth estimates
  - *When these combinations are compared to a notional funding profile, the detrimental impacts of such high reductions over relatively short spans of time become apparent*
  - *Although these compounding variables would likely never be implemented in practice, the top 20th percentile Monte Carlo results provide a good “Rule of Thumb” on how the magnitude of funding reductions must be balanced with the timeframe across which the reductions are applied*

- Regression results indicate that funding reductions implemented earlier in the development cycle may result in reduced cost growth
  - *Trends observed in the Project-level results showed timing of the reduction to be a weaker driver but stronger in the Spacecraft results*

Summary

Deferral Estimation Analysis

- Objective
  - *Develop "Rules of Thumb" to answer the following questions:*
    - For each dollar deferred in year X, what is the increase in development cost and delay in LRD?
      - *Regression results show this to be a far more complicated relationship but do provide guidance on what may be expected based on the historical dataset*
    - When is the optimal point in a project's development to reduce funding in order to minimize the long-term impacts to cost and schedule?
      - *As discussed on the prior slide, funding reductions implemented earlier in the development cycle may result in reduced cost growth, but the trends show a weak correlation*
    - Is there a threshold where the magnitude of a funding reduction results in significantly higher cost and/or schedule growth?
      - *Based on the Monte Carlo regression results, compounding combinations of funding reduction magnitude and the span of time over which the reduction are applied should be limited to less than 12% in any given year to avoid exceeding historical growth trends*
- Caveats
  - *Applications should be limited to sanity checks or high level portfolio analyses*
    - Not intended to serve as a blind estimation model or to replace bottoms up estimates
  - *Application of the Spacecraft and Instrument-level results should be limited until additional data collection and analysis may be completed*

Backup

Agenda

Deferral Estimation Analysis

- Introduction
- Phase 1: Survey of Historical Funding Profiles
  - *Approach and Methodology*
  - *Survey Results*
- Phase 2: Deferred Funding Impacts “Rules of Thumb”
  - *Approach and Methodology*
  - *Regression Results*
  - *Sensitivity Analysis*
  - *“Rules of Thumb”*
- Summary

Phase 1 Survey Results

Deferral Estimation Analysis

- Metrics were collected in two ways:
  - *Absolute data (raw actuals)*
  - *Normalized data (as illustrated below)*
- Metrics were also collected by Phase and WBS
  - *Phase B, C, and D*
  - *WBS: Total Project, PM/SE/MA, Spacecraft, Instruments*

Dependent Variables
Independent Variables

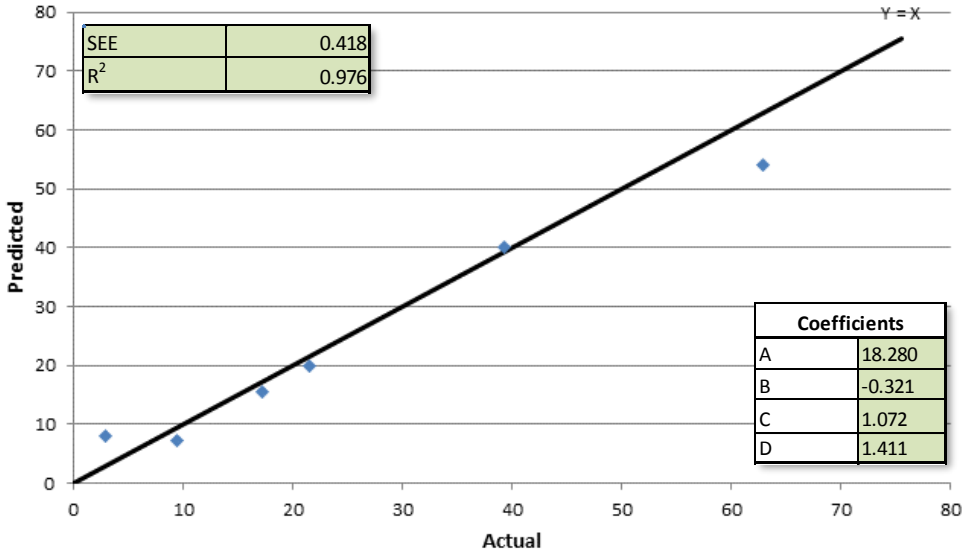
Mission	% Schedule Growth				% Cost Growth				Reduction Timeline % (rel to Phase B Start)					% Funding Reduction	
	Phase B	Phase C	Phase D	Phase B-D	Phase B	Phase C	Phase D	Total	Notification	% Rem Sched After Not	Reduction Start	% Rem Sched After Red Start	Reduction End	Total % Reduction	Current Yr % Reduction
Aquarius	11%	7%	20%	10%	-11%	48%	10%	30%	15%	85%	15%	85%	34%	8%	33%
JUNO	49%	13%	17%	24%	34%	10%	-1%	18%	-34%	133%	-34%	133%	40%	48%	57%
Kepler R1	19%	-2%	-35%	1%	29%	4%	41%	14%	-2%	102%	0%	100%	43%	30%	50%
Kepler R2	0%	61%	-15%	22%	-4%	58%	-19%	30%	33%	66%	33%	66%	49%	6%	18%
OCO	0%	19%	63%	22%	5%	17%	75%	25%	23%	77%	23%	77%	42%	7%	22%
SDO R1	0%	6%	17%	8%	-5%	13%	35%	15%	10%	89%	10%	89%	42%	6%	12%
SDO R2	0%	14%	-8%	6%	0%	9%	-16%	3%	40%	60%	40%	60%	78%	3%	6%
WISE	31%	31%	5%	28%	-5%	55%	38%	39%	4%	96%	4%	96%	21%	9%	27%
GRACE FO	13%	46%	-40%	-2%	15%	56%	-48%	-1%	-9%	109%	23%	77%	43%	2%	11%
ICESat-2 R1	-21%	18%	-33%	-5%	11%	24%	-40%	18%	-38%	138%	-38%	138%	4%	20%	50%
ICESat-2 R2	29%	-2%	0%	5%	24%	-4%	11%	5%	14%	86%	44%	56%	64%	3%	14%
SMAP	57%	42%	13%	39%	12%	14%	-14%	19%	-17%	117%	-17%	117%	32%	34%	46%

* negative growth values represent a reduction

** negative timeline values represent a notification or reduction occurring prior to Phase B start

Spacecraft Cost Growth

Phase 2 Regression Results



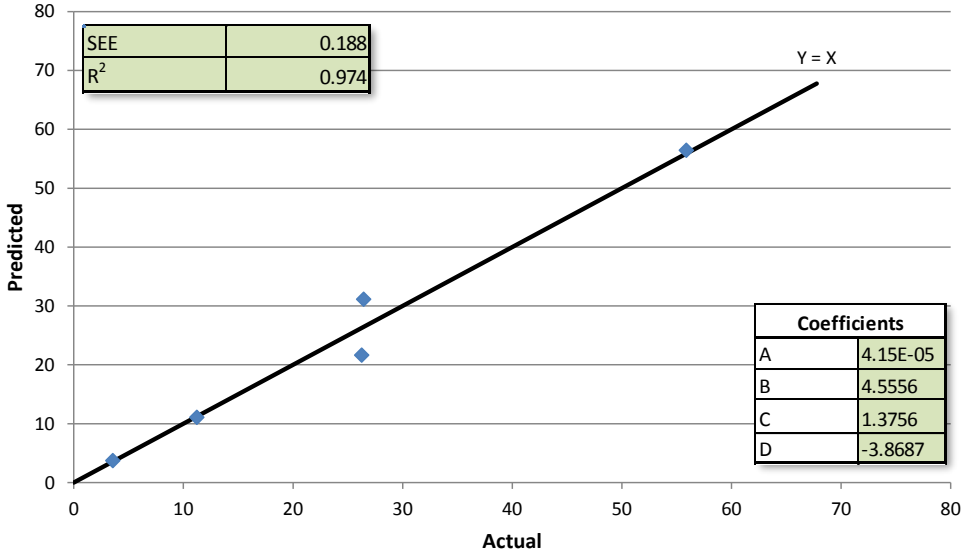
Cost Growth (FY14$M) = 18.28 * Development Cost (FY14$M) $^{-0.32}$ * Total % Reduction $^{1.07}$ * Reduction (phase) $^{1.41}$

- **Independent Variable Definitions**
  - *Development Cost (FY14$M): Phase B-D cost at the applicable WBS in FY14$M*
  - *Total % Reduction = Total Reduction in FY14$M / Development Cost in FY14$M*
    - Total Reduction in FY14$M: In only the year(s) being cut, the sum total of the reduction
  - *Reduction (phase): Development phase in which the reduction will occur*
    - Phase A = 0.25, Phase A/B = 0.375, Phase B = 0.50, Phase B/C = 0.625, Phase C = 0.75

* Pedigree of the historical dataset did not allow data to be collected for all missions at the Spacecraft level (not available for Kepler, OCO, and SDO)

Instrument Cost Growth

Phase 2 Regression Results



Cost Growth (FY14$M) = 4.15x10 $^{-5}$ * Development Cost (FY14$M) $^{4.56}$ * Total % Reduction $^{1.38}$ * Span (mo) $^{-3.87}$

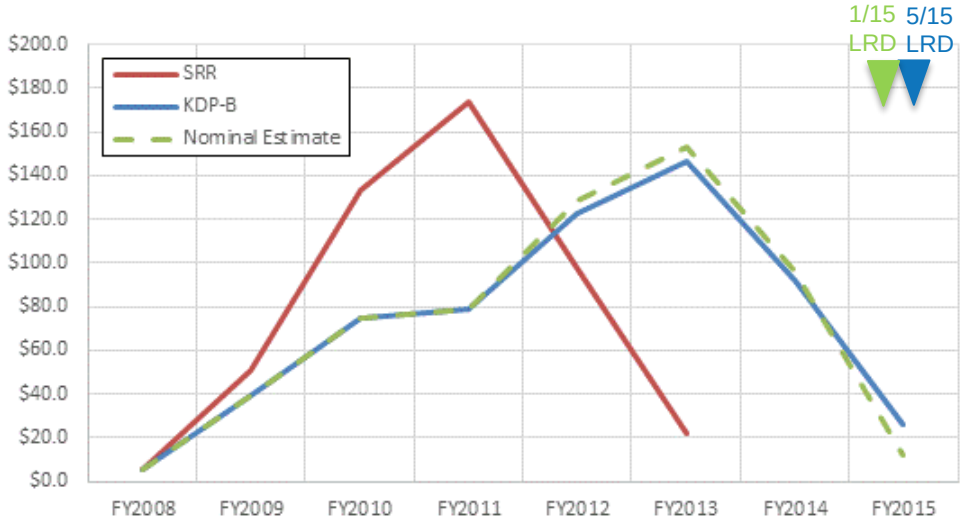
- **Independent Variable Definitions**
  - *Development Cost (FY14$M): Phase B-D cost at the applicable WBS in FY14$M*
  - *Total % Reduction = Total Reduction in FY14$M / Development Cost in FY14$M*
    - Total Reduction in FY14$M: In only the year(s) being cut, the sum total of the reduction
  - *Span (mo): Span in months of the reduction (i.e. if the reduction is to occur in FY16-17, the span is 24 months)*

* Pedigree of the historical dataset did not allow data to be collected for all missions at the Instrument level (not available for Aquarius, Kepler, OCO, and SDO)

Cost and Schedule Growth Estimation (1 of 2)

Nominal Estimate vs. Actual Example

- Nominal Mission Example (Project-Level Analysis)
  - *Cost Growth (FY14$M) = 2.03 * Development Cost (FY14$M)* $^{1.11}$ ** Total % Reduction* $^{1.07}$ ** Reduction (phase)* $^{0.38}$ ** Span (mo)* $^{-1.89}$
    - Development Cost (FY14$M) = $510M
    - Total % Reduction = $175M / $510M = 34%
    - Reduction Phase = Phases A and B = 0.375
    - Span (mo) = 9/30/2011 – 3/1/2009 = 31 mo
  - *Schedule Growth (mo) = 0.34 * Phase B-D Schedule (mo)* $^{0.89}$ ** Development Cost (FY14$M)* $^{0.02}$ ** Total % Reduction* $^{0.82}$ ** Span (mo)* $^{-0.81}$
    - Phase B-D Schedule (mo) = 46.2 mo
    - Development Cost (FY14$M) = $510M
    - Total % Reduction = 34%
    - Span (mo) = 31 mo
  - *Analysis Results*
    - Estimated cost growth is **$99M vs. $95M** actual cost growth
    - Estimate schedule growth is **14 mo vs. 18 mo** actual schedule growth



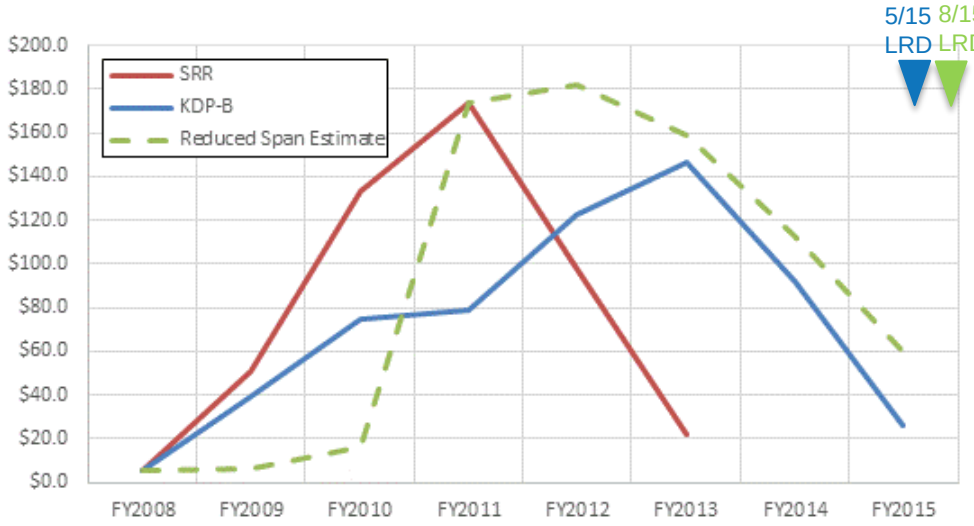
* Estimate profile shape scaled from actual data

Cost and Schedule Growth Estimation (2 of 2)

Hypothetical Estimate vs. Actual Example

- **Reduced Cut** Mission Example
  - *Adjusted Variables*
    - Total % Reduction = **$128M** / $510M = **25%**
  - *Analysis Results*
    - Estimated cost growth is **$71M vs. $95M** actual cost growth
    - Estimate schedule growth is **11 mo vs. 18 mo** actual schedule growth

- **Reduced Span** Mission Example
  - *Adjusted Variables*
    - Span (mo) = 9/30/**2010** – 3/1/2009 = **19 mo**
  - *Analysis Results*
    - Estimated cost growth is **$249M vs. $95M** actual cost growth
    - Estimate schedule growth is **21 mo vs. 18 mo** actual schedule growth



* Estimate profile shape scaled from actual data

AEROSPACE